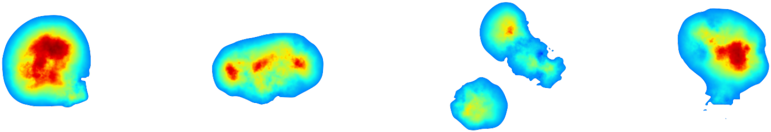
Proton shape fluctuations

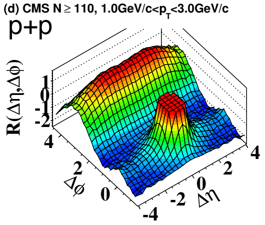
Heikki Mäntysaari

University of Jyväskylä, Department of Physics
Finland

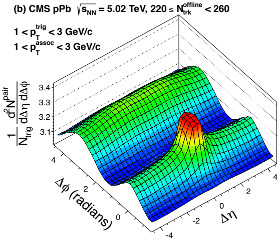


What is the origin of correlations in small systems?

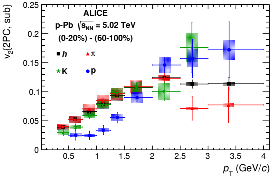
Large long-range correlations in $p+p$ and p+Pb



CMS, JEHP 09 (2010) 091



CMS, PLB 724 (2013) 213



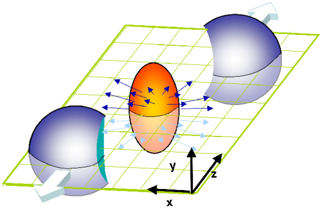
ALICE, PLB 726 (2013) 164

Long range in rapidity, origin from early times, but what?

See also talks by Mace, Gajdosova, Broniowski

In heavy ion collisions: response to initial state geometry

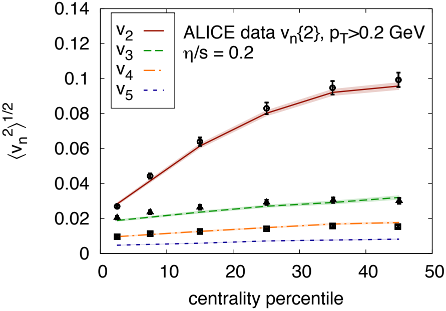
Hydro transforms initial spatial anisotropy ⇒ momentum anisotropy.



Heinz, 0810.05529

Fourier harmonics $\mathbf{v_n}$

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} \sim N_0(1 + 2\mathbf{v_2}\cos(2\phi) + \dots)$$



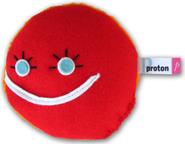
Gale et al, 1209.6330

Also non-trivial proton geometry affecting p+p and p+A measurements?

Going beyond round proton

A fundamental question

How are quarks and gluons distributed spatially?
How do the positions fluctuate?



particlezoo.net

Practical applications to for example

Collective phenomena in $p + A$ and $p + p$ Mäntysaari, Schenke, Shen, Tribedy, Heinz, Singer, Welsh, Moreland, Bernhard, Ke, Bass, Albacete, Petersen, Soto-Ontoso

Exclusive scattering processes Bendova, Krelina, Goncalves,Cepila, Contreras, Takaki; Blaizot, Traini; H.M, Schenke

Elastic $p + p$ and *hollowness* effect Albacete, Soto-Ontoso

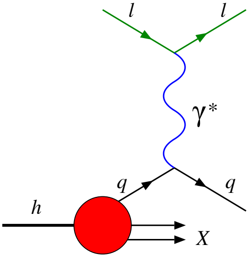
1. Proton shape fluctuations & diffraction

Diffraction

- Scattering with no exchange of net color charge
- Experimental signature: rapidity gap in the detector
- pQCD: at least two-gluon exchange

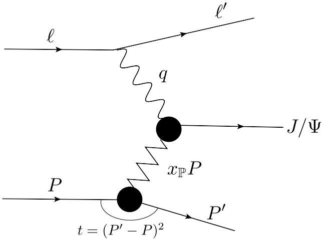
Bendova, Krelina, Goncalves,Cepila, Contreras, Takaki; Blaizot, Traini; Mäntysaari, Schenke

Photon as a simple probe of the proton structure



Deep Inelastic Scattering

- $e + p \to e + X$
- $\sigma \sim$ total (gluon)density
- No t, integrated over geometry



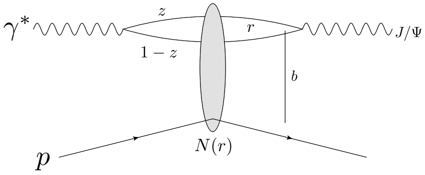
Diffractive vector meson production

- $e + p \to e + p + J/\Psi$
- Can measure total momentum transfer
  - Fourier conjugate to impact parameter
  - Access to spatial density profile

Diffractive vector meson production at high energy

High energy factorization:

1. $\gamma^* \to q\bar{q}$ splitting,
   wave function $\Psi^\gamma(r, Q^2, z)$
2. $q\bar{q}$ dipole scatters elastically:
   $N(r, x, b)$
3. $q\bar{q} \to J/\Psi$,
   wave function $\Psi^V(r, Q^2, z)$



Diffractive scattering amplitude

$$\mathcal{A}^{\gamma^* p \to Vp} \sim \int \mathrm{d}^2 b \mathrm{d}z \mathrm{d}^2 r \Psi^{\gamma^*} \Psi^V(r, Q^2, z) \mathbf{e}^{-i\mathbf{b}\cdot\mathbf{\Delta}} N(r, x, b)$$

- $N(r, x, b)$: dipole-proton scattering amplitude
- Impact parameter is the Fourier conjugate to the momentum transfer $(-t \approx \Delta^2) \to$ access to the spatial structure

Proton shape from coherent diffraction

Coherent cross section, Good, Walker, PRD 120, 1960

Average interaction of states that diagonalize the scattering matrix

- These states are $q\bar{q}$ dipoles with fixed size $\mathbf{r}$, probing fixed target configuration Ω
- Target remains in the same quantum state

Coherent cross section

$$\frac{\mathrm{d}\sigma^{\gamma^* A \to VA}}{\mathrm{d}t} \sim |\langle \mathcal{A}^{\gamma^* A \to VA} \rangle_\Omega|^2$$

- Cross section probes average $\mathbf{b}$ dependence of the scattering amplitude = target geometry

$$\langle \mathcal{A}^{\gamma^* p \to Vp} \rangle_\Omega \sim \int \mathrm{d}^2\mathbf{b}\,\mathrm{d}z\,\mathrm{d}^2\mathbf{r}\,\Psi^{\gamma^*}\Psi^{V}(|\mathbf{r}|, z, Q^2)\,\mathbf{e}^{-i\mathbf{b}\cdot\boldsymbol{\Delta}} \langle N(|\mathbf{r}|, x, \mathbf{b}) \rangle_\Omega$$

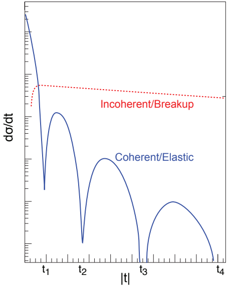
Incoherent diffraction = target dissociation

Incoherent cross section

- Target final state $|f\rangle \neq$ initial state $|i\rangle$
- No net color charge transfer
- Rapidity gap between J/Ψ and target remnants

$$\sigma_{\text{incoherent}} \sim \sum_{f \neq i} |\langle f|\mathcal{A}|i\rangle|^2$$

$$= \sum_f \langle i|\mathcal{A}|f\rangle^\dagger \langle f|\mathcal{A}|i\rangle - \langle i|\mathcal{A}|i\rangle^\dagger \langle i|\mathcal{A}|i\rangle$$



Average over initial states:

$$\sigma_{\text{incoherent}} \sim \langle |\mathcal{A}|^2 \rangle_\Omega - |\langle \mathcal{A} \rangle_\Omega|^2$$

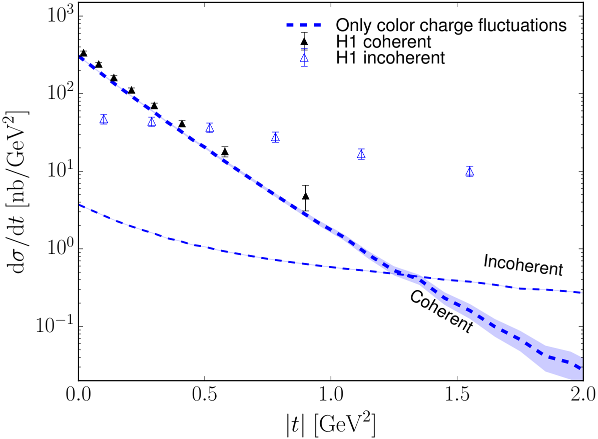
Incoherent cross section = variance of $\mathcal{A}^{\gamma^* A \to VA}$

- Amount of event-by-event fluctuations in target configurations Ω

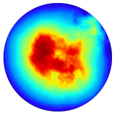
Miettinen, Pumplin, PRD 18, 1978, Caldwell, Kowalski, Phys.Rev. C81 (2010) 025203

Proton shape from diffraction: $\gamma + p \to J/\Psi + p$

HERA data with only color charge fluctuations ($x \sim 10^{-3}$)



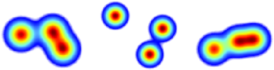
Round CGC proton: Color charges +Yang-Mills



H.M, B. Schenke, 1607.01711, H1: 1304.5162

Constraining proton fluctuations

Simple constituent quark inspired picture:



- Sample quark positions from a Gaussian distribution (width B_{qc})
- Small-x gluons are located around the valence quarks (width B_q).
- Combination of B_{qc} and B_q sets the degree of geometric fluctuations

Now proton = 3 overlapping hot spots.

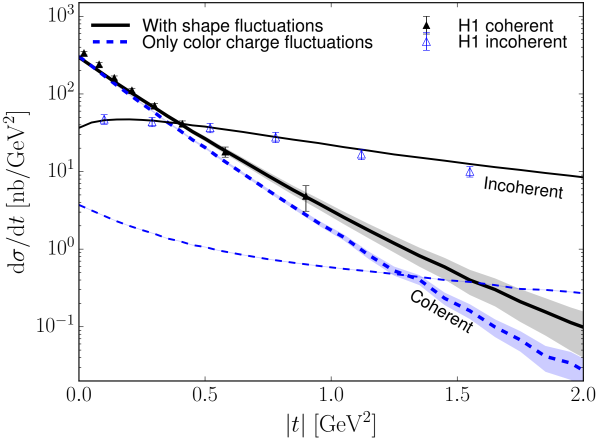
$$T_{\mathrm{proton}}(b) = \sum_{i=1}^{3} T_q(b - b_i) \qquad T_q(b) \sim e^{-b^2/(2B_q)}$$

+ density fluctuations for each hot spot

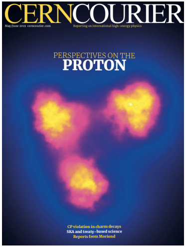
H.M, Schenke, 1607.01711, 1603.04349, also more complicated geometries

Similar setup e.g. in Bendova, Cepila, Contreras; Cepila, Contreras, Krelina, Takaki; Traini, Blaizot

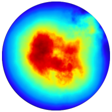
Constraining proton fluctuations: $\gamma + p \to J/\Psi + p$



Fluctuations



Round



HERA data requires large event-by-event fluctuations

H.M, B. Schenke, 1607.01711

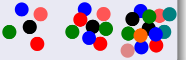
Bjorken-x dependence

Approach 1: parametrize number of hot spots

Small-x gluon emissions increase the number of hot spots

Cepila, Contreras, Tapia Takaki, 1608.07559

$$N_{hs}(x) \sim x^{p_1}(1 + p_2\sqrt{x})$$



Approach 2: Solve small-x evolution equations

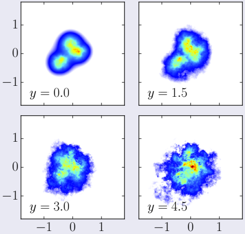
Evolve proton structure by solving

- BK evolution with impact parameter

  Berger, Stasto, 1106.5740, Cepila, Contreras, Matas, 1812.02548

- JIMWLK evolution

  Schlichting, Schenke, 1407.8458, H.M., Schenke, 1806.06783

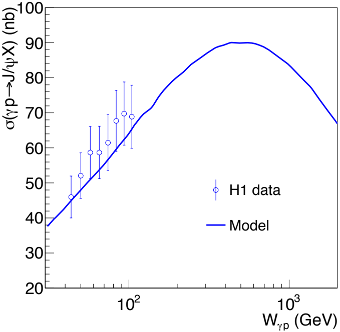


Fit HERA F_2 and exlusive data.
Difficulty: regulating confinement effects

Towards small x: $\gamma + p \to J/\Psi + p^*$

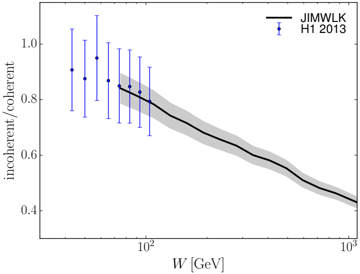
Increasing # of hot spots w energy:
Smoother proton, less fluctuations

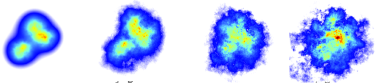
Cepila, Contreras, Tapia Takaki, 1608.07559



JIMWLK evolution event-by-event
Includes also growing RMS size

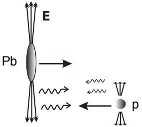
H.M., Schenke, 1806.06783





Exclusive J/Ψ production at small x at the LHC

Ultraperipheral $p+A$:
Photon flux $\sim Z^2$
$\gamma + p$ dominates

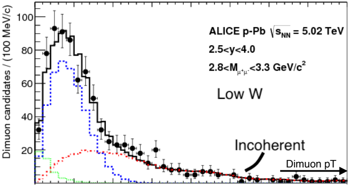


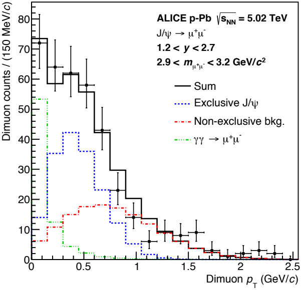
Larger COM energies:
incoherent $\rightarrow$ 0 (?)
$\Rightarrow$ smoother proton?

ALICE:1809.03235

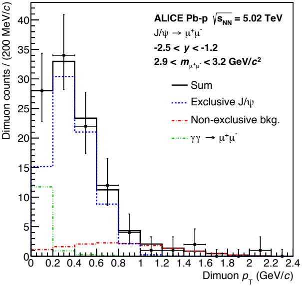
Low energy $\gamma - A$: coherent and incoherent visible

ALICE: 1406.7819





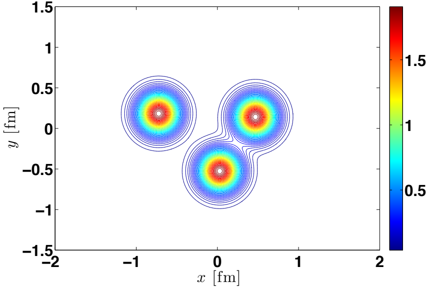
Medium E



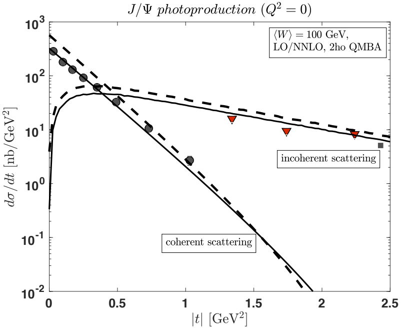
Large E

Improvements to the hot spot picture

Quark position correlations included in Traini, Blaizot, 1804.06110
Less free parameters, still good description of the HERA data



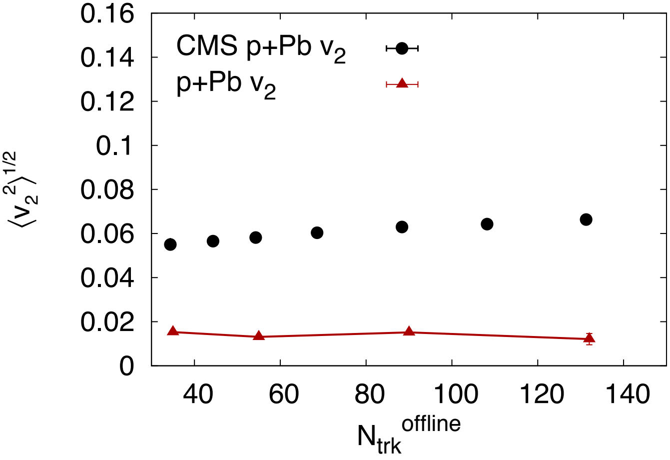
Traini, Blaizot, 1804.06110



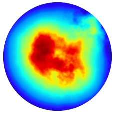
Traini, Blaizot, 1804.06110

Implications on heavy ion phenomenology: p+A

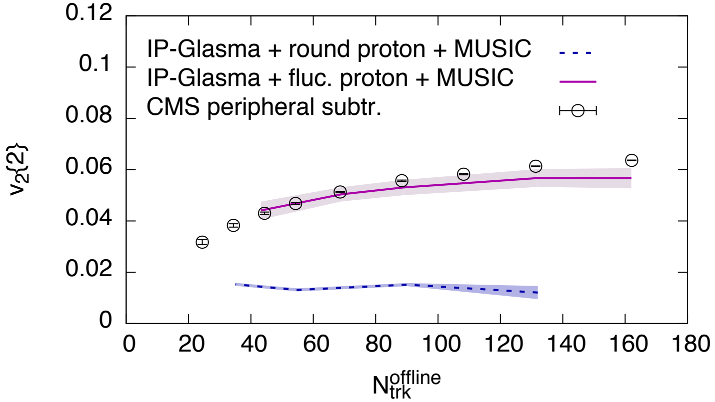
Round protons: hydro simulations can not describe v_2 in $p + Pb$ collisions
IP-Glasma, Schenke, Venugopalan, 1405.3605: need eccentric protons

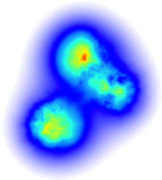


Round



Hydro + fluctuations from HERA J/Ψ data: success

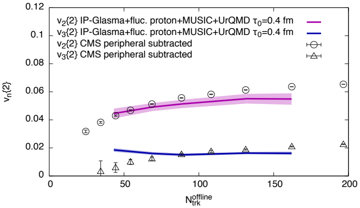


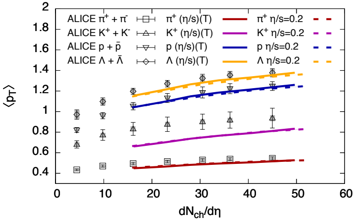


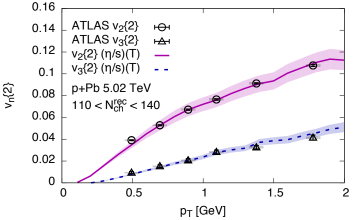
H.M, Schenke, Shen, Tribedy, 1705.03177

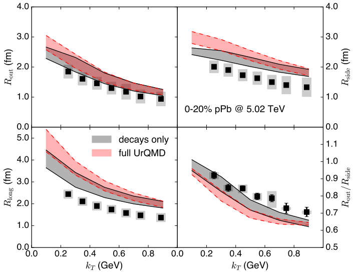
Implications on heavy ion phenomenology: p+A

Hydro + fluctuations from HERA J/Ψ data: success







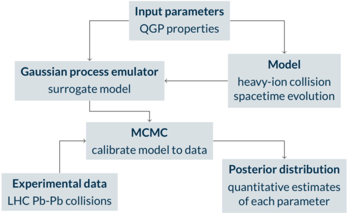


H.M, Schenke, Shen, Tribedy, 1705.03177

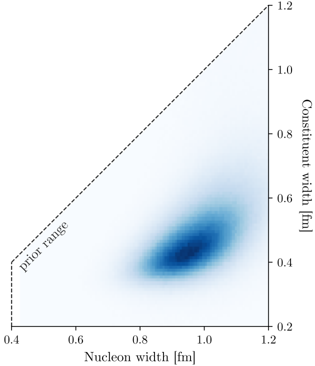
2. Other approaches to proton shape fluctuations

Fluctuations from $p + A$ data

Extract proton fluctuations from hydro simulations of p+Pb and Pb+Pb
Apply Bayesian methodology



$\Rightarrow$

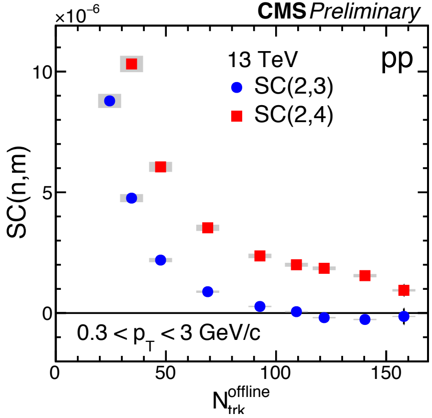


Find also large fluctuations in the proton, but slightly different:
Larger proton, bigger hot spots. But energy deposit $\neq p$ density profile

Moreland, Bernhard, Ke, Bass, QM2017 and 1704.04486, Moreland, Bernhard, Bass, 1808.02106, talk by Bass today

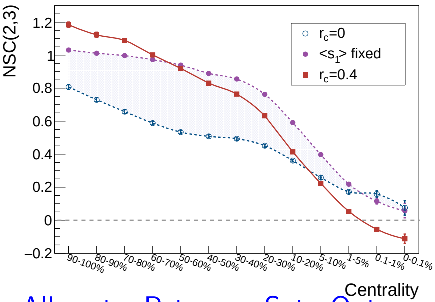
Symmetric cumulants in $p + p$

CMS: in central $p + p$ correlation between v_2 and v_3 becomes negative
Explained: fluctuating hot spots + short range repulsive correlations
CMS: $SC(2,3) < 0$ in central $p + p$



CMS-PAS-HIN-16-022, see also ALICE, 1903.01790

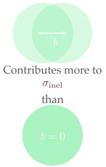
Sign change with 3 hot spots + nonzero repulsive distance r_c



Albacete, Petersen, Soto-Ontoso, 1707.05592

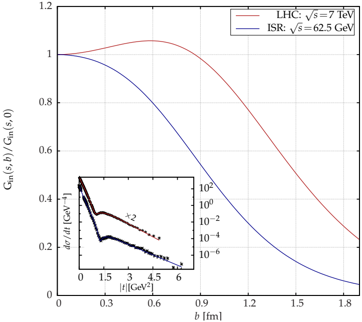
Short range correlations and the Hollowness effect

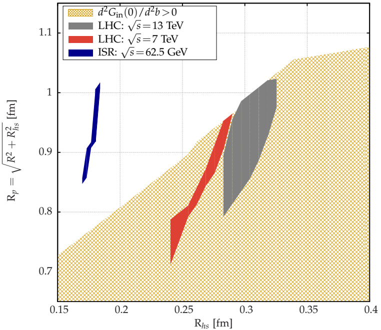
Hollowness effect seen in elastic p+p scattering at LHC energies:



J. Albacete,

IS2016





With short range repulsive correlations, can constrain

- Proton size R_p
- Hot spots size R_{hs}

Albacete, Soto-Ontoso, 1605.09176

Conclusions

Strong hints from HERA and LHC data that

- Proton geometry has large event-by-event fluctuations
- Fluctuations evolve in x

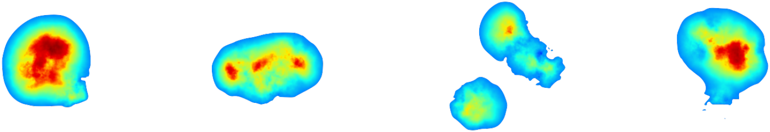
Multi dimensional event-by-event picture of the proton

- Input from (diffractive) DIS, applications on heavy ion (or p+p) phenomenology
- Or vice versa...

New interesting data coming

- Ultraperipheral collisions at the LHC

  See also M. Walczak, Tue 17:40, ALICE, ATLAS, CMS, LHCb summaries on Mon
- Electron Ion Collider See also J. H. Lee, Wed 18:10



BACKUPS

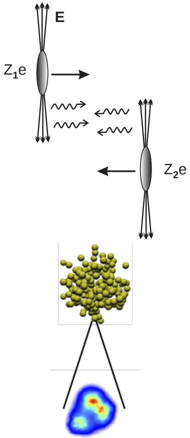
Diffraction in ultraperipheral collisions

Ultra Peripheral heavy ion Collisions (UPC):
access to photonuclear reactions

- At $|b_T| > 2R_A$ one nucleus acts as a photon source

Two sources of fluctuations:

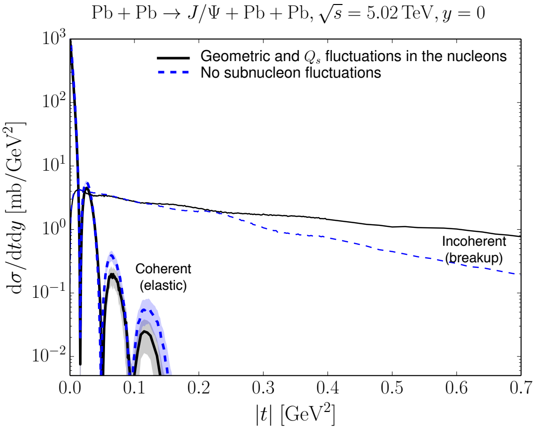
- Nucleon positions from Woods-Saxon
- Constituent quark structure for each nucleon



Exclusive J/Ψ production: probe both components

Accessing fluctuations at different scales

LHC: Access nuclear gluon at very small x, midrapidity $x_p \approx 6 \cdot 10^{-4}$



Generically

- $\sqrt{|t|}$ is conjugate to b_T
- Small $|t|$: fluctuations at nucleon scale
- Large $|t|$: fluctuations at subnucleon scale

LHC: see nucleon scale fluctuations in Pb

H.M, Schenke, 1703.09256; Cepila, Contreras, Krelina, 1711.01855:

ALICE UPC data (1406.7819) seems to prefer subnucleon fluctuations